Towards a Definition of Representational Competence

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Currently, there is not a consensus in science education regarding representational competence as a unified theoretical framework. There are multiple theories of representational competence in the literature that use differing perspectives on what competence means and entails. Furthermore, dependent largely on the discipline, language discrepancies cause a potential barrier for merging ideas and pushing forward in this area. In science, representations are used to display data, organize complex information, and promote a shared understanding of scientific phenomena. As such, for the purposes of this text, we define representational competence as a way of describing how a person uses a variety of perceptions of reality to make sense of and communicate understandings. While a single unified theory may not be a realistic goal, strides need to be taken towards working as a unified research community to better investigate and interpret representational competence. Thus, this chapter will define aspects of representational competence, modes of representations, and the role of a representational competence theoretical framework in science education research and practice.

Science is often communicated via visual means, be it graphs, tables, models, diagrams, or simulations. This style of communication relies on the intended receiver's ability to make sense of the visual inputs in manners consistent with scientific thinking. With growing access to technology and its continued integration into educational environments (laptops, tablets, smartphones, desktop monitors, etc.), there is a growing trend that students are being exposed to even more science visualizations as a means of communicating ideas. It is becoming ever more critical to understand how to best help students learn using visualizations in science. Through investigating and discussing the role of representational competence in students' science learning we can better understand how to help students use science visualizations.

This book serves to initiate thinking about a representational competence theoretical framework across science educators, learning scientists, practitioners and scientists as well as provide a current state of thinking about representational competence in science education. Authors in the following chapters pose new questions to consider and explore ideas linked to representational competence in science education with regards to external visualizations as we press forward in advancing our field through research, and bridge thoughts across disciplines.

Background and Theory

Representations are useful tools that organize complex information, display data, and elaborate on complex topics in ways that make the information easier to understand. Representations are critical for communicating abstract science concepts (Gilbert, 2005), where there can be vast amounts of data or phenomena that when written in text, can lead to misconceptions. Ignoring how students use and develop scientific representations will prevent them from developing expertise in their field. Rather we need to focus on understanding how students learn to interact and communicate with scientific representations.

There are two primary types of representations: external and internal. External representations are visually perceivable models while internal representations result from perceptions that remain inside the mind. The distinction between these representation types is sometimes blurred by the assumption that the focus of cognitive research is ultimately on internal representations. The classification of pictorial and verbal representations constructed by students can be used as an assessment tool to help represent internal representations or mental models held and used by students. All the same, understanding the nature and role of external representations in content areas is important when investigating instruction and learning, because external representations themselves can be a significant component of reasoning within that domain. When learning with representations, there are two frameworks that capture and explain STEM learning with visualizations as learners develop expertise, representational competence and model competence.

Representational competence is a way of describing how a person uses a variety of perceptions of reality to make sense of and communicate understanding through external visualization (Halverson & Friedrichsen, 2013; Kozma & Russell, 2005). To determine students' representational competence, representational fluency must also be addressed. Representational fluency is a measure of representational competence, and is the process of translating and moving within and between representations to understand a concept. While representational competence is static, representational fluency is the students' ability to seamlessly move within and between representations, ultimately increasing learning.

Representations can be expressed though five external forms: concrete, verbal, symbolic, visual, and gestural (Gilbert, 2005). These forms of fluency are explored more in depth in chapter two, in which the understanding of STEM concepts rests with the learner's ability to represent these concepts and then translate between and within representational forms. When a learner achieves high representational competence, he/she can begin shifting the external representation into an internal representation, or a mental image that can be manipulated to improve performance on visual tasks, memory tasks, and cognitive problem solving (Gilbert, 2005; Botzer & Reiner, 2005; Clement, Zietsman, & Monaghan, 2005). Competence can then be investigated as an outcome, condition, or developmental stage with students' understanding of content based on their interactions with representations.

Where representational competence is a way of describing a learner's ability to use representations, model competence describes how a person interacts with a representation either as a medium (to interpret or illustrate meaning) or a method (a process to test or make predictions about questions) (Upmeier zu Belzen & Krüger, 2010). This competence can be measured by capturing data on how effectively a person completes varying tasks. Developing high representational and model competence does not happen overnight. Students enter the classroom with preconceptions about many topics and these preconceptions can influence their understanding of how to internalize, interpret, and interact with external visualizations (Meir, Perry, Herron, & Kingsolver, 2007). It is possible for a learner's level of representational competence to change based on content (Gilbert, 2005) and task difficulty. Therefore, it is critical to consider how students use and make sense of representations depicting science content.

Visual representations play a key role in mathematics, geography, and science (Cuoco & Curcio, 2001; Gilbert, 2005) and can be considered a means to form conceptual understanding (Zazkis & Liljedahl, 2004). We know that visualizations can enhance learning from texts, improve problem solving, and facilitate connections between new knowledge and prior knowledge (Cook, 2006). Various forms of visual representations can support an understanding of different, yet overlapping, aspects of a phenomenon or entity. While there is no doubt that the use of visual representations enhances learning (Cook, 2006; Meyer, 2001; Peterson, 1994; Reiner & Gilbert, 2008; Woleck, 2001) students' ability to comprehend and interact with visual representations is often found lagging (Zbiek, Heid, Blume, & Dick, 2007; Anderson & Leinhardt, 2002; Ferk, Vrtacnik, Blejec, & Gril, 2003; Reiss & Tunnicliffe, 2001; Tufte, 2001). In science, the National Research Council (1996) outlined the following objectives for students working with representations. Students should be able to:

- Describe and represent relationships with visual representations;
- Analyze relationships and explain how a change in an entity affects another;
- Systematically collect, organize, and describe data;
- Describe and compare phenomena;
- Construct, read, and interpret representations;
- Support hypotheses and argument with data;
- Evaluate arguments based on data presented;

- Represent situations with multiple external visual representations and explore the interrelationship of these representations; and
- Analyze representations to identify properties and relationships.

When visual representations are understood accurately, they can provide depictions of phenomena that cannot be illustrated through other approaches. In some cases, visual representations can be misleading and create additional difficulties with interpretation (Zbiek, Heid, Blume, & Dick, 2007; Tufte, 2001). This is often the case when students use representations as a literal depiction of the phenomenon (Anderson & Leinhardt, 2002). For example, children learning anatomy sometimes view symbolic references of a heart as a realistic expectation to how an anatomical heart will appear (Reiss & Tunnicliffe, 2001). However, before we can fully begin to understand how students use and interact with representations we need to recognize the different ways different scientific content areas approach representations. Chapters in this book cover aspects of representational competence within multiple science domains.

A Chance to Reach Consensus

Understanding how representations are interpreted in different content areas begs the question, can we reach a consensus of how representations influence learning?

Implications for Thinking

Research has shown that students have difficulties identifying key structures of visual representations, interpreting and using visual representations, transitioning among different modes of representations (e.g., 2D and 3D models), relating abstract representations to content knowledge, and understanding what approaches are appropriate for making sense of representations (Ferk, Vrtacnik, Blejec, & Gril, 2003; Gabel, 1999; Hinton & Nakhleh, 1999; Johnstone, 1993; Treagust, Chittleborough, & Mamiala, 2003). Sometimes, the way students make sense of a visualization may lead to correct responses, but this does not mean that the students have used an appropriate approach (Tabachneck, Leonardo, & Simon, 1994; Trouche, 2005). Experts are able to organize knowledge from visual representations into patterns that inform actions and strategies, while novice students rely upon superficial knowledge of equations and representations rather than patterns to generate solutions (Bransford, Brown & Cocking, 1999; Larkin, McDermott, Simon, & Simon, 1980). For students to become experts with visualizations, they must learn how to interpret visualizations correctly and use them as a reasoning tool when investigating problems (Cavallo, 1996).

An example of this difficulty in developing expertise with visualizations has been documented in evolutionary biology. In this domain, phylogenetic trees use branches and nodes to represent hypothesized relationships among species by mapping descent from common ancestry. Phylogenetic trees can be verbally explained to assist with interpretation. However, it is difficult to represent relationships among organisms at the same level of detail without using a visualization. For example, patterns of monophyletic groups (a common ancestor and all descended lineages, also referred to as a clade) and genetic algorithms (evolutionary computations used to identify optimality) are difficult to comprehend without a visual or symbolic image. This process of using a phylogenetic approach to understand evolutionary biology is referred to as tree-thinking (Baum & Smith, 2013). Within tree-thinking, there are two core skill sets required for understanding these trees: tree reading and tree building (Halverson, 2011).

Experts in systematics are identified by their ability to comprehend phylogenetic trees as representations of species relatedness and are able to use trees as reasoning tools when solving systematics problems. They use phylogenetic representations to interpret and illustrate patterns among the evolutionary histories of different species lineages. Thus, understanding phylogenetic trees involves overcoming prior naïve ideas about species and interpreting relations based on the branching patterns of the tree. It is imperative that students are able to interpret and recognize patterns when processing evolutionary trees. If students cannot recognize patterns within phylogenetic trees, then they will not be able to accurately interpret the intended meaning nor test the hypothesis presented. Thus, it is critical that learners are assisted with learning how to recognize patterns, particularly in scientific visualizations (Anderson & Leinhardt, 2002; Tabachneck, Leonardo, & Simon, 1994; Simon, Larkin, McDermott, & Simon, 1989).

Interpreting visual phylogenetics representations often depends more on pattern recognition than on conceptual understanding. Given student explanations of their reasoning processes, they seem to misinterpret trees because of flawed reasoning in pattern recognition (e.g., associating species proximity to each other as relatedness) (Baum, Smith, & Donovan, 2005; Gendron, 2000; Gregory, 2008; Meisel, 2010; Meir, Perry, Herron, & Kingsolver, 2007) or incorporating foundational misconceptions about evolution into tree thinking (Halverson, Pires, & Abell, 2011; Gibson & Hoefnagels, 2015; Walter, Halverson, & Boyce, 2013). Part of the issue might be due to students not accessing information visually presented by a tree to make sense of a given problem. However, we are just now accessing biometric data that offers evidence for how experts or novices visually access information gleaned from tree diagrams.

Relatively new, emerging technology now allows investigators to gather biometric data about eye movement patterns and interactions with visual stimuli.

The process of recording and measuring eye movement patterns, called eye-tracking, is used in a variety of disciplines (Duchowski, 2002) and can aid representational competence researchers identify how information is visual accessed. Eye-tracking is frequently used in reading comprehension studies (Rayner, 2009), but its application in science education is growing. For example, using eye-tracking technology to gather biometric data has helped evolutionary biologists understand how students are visually interacting with phylogenetic tree diagrams (Novick, Stull, & Catley, 2012). Chapter 11 explores the use of eye-tracking as a means for assessing and understanding visual attention while using representations in science education. The information in chapter 11 synthesizes prior use of this tool as well as providing insight towards future research for using eye-tracking as way to assess representational competence.

A more tradition way to assess students' level of representational competence is through qualitative methods. Interviewing students or collecting data via open-ended questionnaires can provide an in depth understanding of a student's level of representational competence. For example, qualitative methods were instrumental in documenting the inventory of common tree-thinking misconceptions (Gregory, 2008; Halverson, Pires, & Abell, 2011). However, qualitative means are not always time efficient for classroom use, nor when assessing large groups of students. In these instances, quantitative means would be more efficient. Quantitative assessment assigns a numerical value, usually on a scale, to indicate a level of progress or competency. In the case of tree-thinking, one skill that can easily be quantified in relation to competency is visualization of rotation. Mental rotation has been linked to students' ability to succeed in topics stemming from spatial ability (Bodner & Guay, 1997). There is evidence that ability to think visually and manipulate images is linked to problem solving in chemistry (Stieff & Raje, 2010; Stieff, 2007). Unfortunately, visual-spatial thinking is often overlooked by science educators (Mathewson, 1999). Although we see evidence of the role of mental rotation in many areas of science and medicine, only preliminary studies have quantitatively measured students' visualization of rotation using a multiple choice quantitative instrument (Bodner & Guay, 1997) and examined at how it impacts learning with visualizations in biology (Maroo & Halverson, 2011). Tree-thinking requires mental rotation skills as phylogenetic trees are often presented as two dimensional representations, but requires processing in three dimensional space in order to interpret and compare diagrams (Halverson, 2010). This rotational aspect of these trees is comparable to that of molecular models seen in chemistry. And difficulties with mental rotation can lead to challenges in developing expertise in representational competence. More details on assessing representational competence is discussed in Section C of this book.

Call to Measure Representational Competence Across Disciplines

There is a need to investigate representational competence across domains. Information visualization is crucial for processes of high level cognition and communication (including education, decision-making, and scientific inquiry), with separate visualization traditions established in these respectful fields (Roundtree 2013; Skupin 2011). For example, in geography, visual depiction and analysis of spatial relationships is often the core of the scientific study in question, including natural and human phenomena. In biology, phylogenetic trees and maps of species distribution are meant to teach and communicate relationships between classes within kingdoms of species. In computer science, proximity of blocks of code and 3D animations can aid the learnability of interfaces, as well as illustrate interrelationships between computer program sub-functions. In chemistry, atomic models use proximity to depict visual representations of interactions between individual elements. Despite obvious parallels between these fields, no cross-domain theory of visual cognition and communication exists to date. Exploring ways to synthesize and evaluate a set of fundamental cross-discipline visualization principles that enable human comprehension and valuation, moving past research into visual perception towards the science of visual cognition would greatly improve visual communication design and education in natural, theoretical and applied sciences (Fabrikant & Skupin, 2005; Rayl 2015).

Looking forward, there is also justification for research into ways visual communication can impact English Language Learners (ELL) and visually impaired students learning. Understanding how visualizations affect learning in these communities of students can provide a more thorough and inclusive learning environment in the classroom. Specifically, exploring how underrepresented student groups like ELL and visually impaired students interact with visualizations might provide educators with key insight for increasing learning opportunities for these students. For example, consider such use as 3D printing to create and adapt a manipulative model that would serve as a tactile aid for students who cannot see visual models or that may have other cognitive learning abilities. Such modifications could lead to increased representational competence for these students. Regardless of specific content area, there are many opportunities to investigate how representations are used in the classroom and how educators can integrate more inclusive representational forms for all students.

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